

## PERSPECTIVES: BLACK HOLES

When asked to discuss Cyg XR-1, E. E. Salpeter once concluded, "A black hole in Cyg X(R)-1 is the most conservative hypothesis." [1] Recent observations now make it likely that a black hole in Cyg XR-1 is the only hypothesis tenable.

Chandrasekhar first showed [2] that compact stars - those with the inward force of gravity on their outer layers balanced by the pressure generated by the Pauli exclusion principle acting on its electrons (in white dwarfs) or nucleons (in neutron stars) - have a maximum mass. Equilibrium is achieved at a minimum of the total energy of the star, which is the sum of the positive Fermi energy and the negative gravitational energy. The maximum mass attainable in equilibrium is found by setting  $E = 0$ :  $M(\text{max}) \sim 1.5 M(\text{Sun})$ . If the mass of the star is larger than this, then  $E$  can be decreased without bound by decreasing the star's radius and increasing its (negative) gravitational energy. No equilibrium value of the radius exist, and general relativity predicts that gravitational collapse to a point occurs. This point singularity is a black hole.

The black hole singularity is not visible to the outside world, however. The metric in general relativity outside an uncharged point mass  $M$  was found by Schwarzschild [3] to have a singularity in its radial co-ordinate at distance  $R(S) = 2GM/c^2 \sim 3 M/M(\text{Sun}) \text{ km}$ . (In addition, the time co-ordinate goes to zero at this distance.)  $R(S)$  is known

as the Schwarzschild radius, and no signal can reach the region of space-time outside this radius from the region inside. The boundary between the two regions is called the event horizon. Any black hole will have an event horizon, so the naked point singularity is forever shielded from our view. Contrariwise, any object with an event horizon must be a black hole.

Salpeter's remark was based on observations of Cyg XR-1 and other X-ray binary systems that showed the X-ray source to be a compact object with a minimum mass above  $M(\max)$ . ( $M > 6 M(\text{Sun})$  for Cyg XR-1. [4]) This ruled out a white dwarf or neutron star as the compact object, but still allowed more unusual objects, such as a Q star. [5] Two recent observations may now have detected the presence of an event horizon in X-ray binary systems, making the identification of stellar-mass sized black holes all but certain.

In the first, M. Garcia et al. [6] used the Chandra satellite to monitor the X-ray luminosity of six candidate black-hole transients in quiescence. (Transient X-ray sources exhibit weeks-long episodes of outburst separated by long periods of extremely low luminosity, a behavior connected to episodic mass transfer from a companion star.) Garcia et al. found quiescent black-hole transients to be 1/100th as luminous in X-rays as quiescent neutron-star transients with similar orbital periods. They interpret the effect as being caused by most of the radiation generated locally in the quiescent accretion disk disappearing across

the event horizon of the black hole.

This detection of an event horizon depends on knowing the local luminosity that the system produces in the accretion disk for comparison purposes. Garcia et al. assume an advection-dominated accretion flow (ADAF) model of the disk to calculate its local luminosity. Some question has been raised as to whether an advection-dominated input-output system (ADIOS) may not be operating in transients during quiescence. In this case, most of the energy generated by accretion would be carried away from the central object by mass outflow above and below the plane of the disk. The accreting object would still be a black hole, but the low luminosity observed would not be directly related to the existence of an event horizon. Theoretical work continues on the nature of the accretion in black-hole transients.

In the other observation, J. F. Dolan [7] analyzed High Speed Photometer (HSP) data from Cyg XR-1 obtained with the Hubble Space Telescope (HST). (The HSP was the instrument removed from HST in 1993 in order to install corrective optics for HST's spherically aberrated primary mirror.) He detected two series of pulses in the ultraviolet that had the characteristics of dying pulse trains, the signature of material falling into the event horizon from the inner edge of the accretion disk. (The inner edge is defined by the last stable Keplerian orbit around the black hole at  $3 R(S)$ .) The dying pulse train phenomenon was predicted by W. R. Stoeger, S.J. in 1980 [8]. Individual flare patches - clumps of material whose radiative characteristics stand

out above the mean flux of the system - are seen to emit pulses because their radiation is aberrated away from the direction to the Earth when they orbit on the far side of the black hole (see the figure). The separation between pulses decreases as the material spirals into the event horizon. The peak intensity of the pulses also decreases as the material approaches the event horizon because of the Doppler effect in the gravitational potential well of the black hole. The last visible pulse is the weakest; if the accreting object had a solid surface, like a neutron star, the last pulse would be the largest as the material impacted the surface. The observed phenomenon is a signature of an event horizon, but Dolan points out that the statistical confidence level in the pulses not being stochastic variations in the flux is not high enough to convict Cyg XR-1 of being a black hole beyond a reasonable doubt. (If even one of the first four pulses in a series were only a random variation in the flux, then the characteristics of the other pulses in the series would no longer match those of a dying pulse train.) Further observations of Cyg XR-1 in the X-ray and UV regions are planned; if dying pulse trains are present, they should be confirmed by these observations.

Other theories of gravity that are also consistent with the classical tests of general relativity [9] do not predict the existence of black holes and event horizons. If the orbital topography near compact objects in these competing theories can not produce a way to mimic these observations, the

detection of event horizons may be another successful test of the validity of general relativity.

## REFERENCES

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FIGURE CAPTION

Dying pulse trains. A luminous clump of material detaching from the inner edge of the accretion disk spirals into the event horizon and disappears. The photometric signature of its emission is shown below.

## Signature of piece of matter falling into black hole Cygnus XR-1

Disk of spiraling hot gas

Black hole event horizon

1000-mile gap



Blob of gas breaks off disk to spiral toward event horizon

## Ultraviolet light signature of dying pulse train seen near event horizon

Brightness



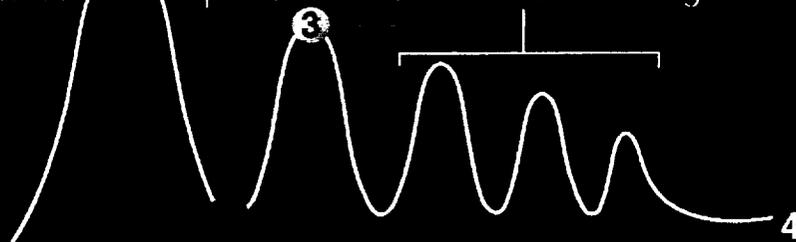
Blob leaves disk, begins to spiral inward



Blob brightens but does not return to same point in orbit



Pulse duration shortens as blob spirals inward; blob fades due to gravitational redshift of light



Blob dims on far side of event horizon

Blob disappears due to gravitational redshift of light as it continues to spiral toward event horizon

Time